WOLF–RAYET STARS AND RADIOISOTOPE PRODUCTION

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Radioisotopes are natural clocks which can be used to estimate the age of the solar system and of the Universe (see e.g. Takahashi 1998; Chen & Tilton 1976; see also the recent review by Arnould & Takahashi 1999). They are responsible for the steady decline of the light curves of supernovae (see e.g. Diehl & Timmes 1998, and references therein). The diffuse emission at 1.8 MeV from the decay of ^{26}Al (e.g. Arnould & Prantzos for a recent review) may also provide a measure of the present day nucleosynthetic activity in our Galaxy. Therefore, even if radionuclides represent only a tiny fraction of the cosmic matter, they carry unique pieces of information.

A great number of radioisotopes are produced by massive stars at the time of the supernova explosion. A fraction of them are also produced during the previous hydrostatic burning phases. These nuclides are then ejected either at the time of the supernova event, or through stellar winds during the hydrostatic burning phases. This paper focusses on the non-explosive ejection of radionuclides by Wolf-Rayet (W–R) stars.

1 THE W–R STARS

Wolf-Rayet stars are generally believed to be bare cores of initially massive stars (Lamers et al 1991) whose original H–rich envelope has been removed by stellar winds or through a Roche lobe overflow in a close binary system (see the recent reviews by van der Hucht 1992; Maeder & Conti 1994; Willis 1999). Observationally, most W–R stars appear to originate from stars initially more massive than about 40 $M_\odot$ (Conti et al 1983; Conti 1984). Some of them, however, may have progenitors with initial masses as low as 15–25 $M_\odot$ (see e.g. Hamann & Koesterke 1998; Massey & Johnson 1998). The stars enter the W–R phase as WN stars whose surface abundances are representative of equilibrium CNO processed material. If the peeling off proceeds deep enough, the star may enter the WC phase, during which the He–burning products appear at the surface.

Many observed features are well reproduced by current stellar models. Typically, good agreement is obtained between the observed and predicted values for the surface abundances

of WN stars (Crowther et al 1995; Hamann & Koesterke 1998a). This indicates the general correctness of our understanding of the CNO cycle (Maeder 1983), but is not a test of the model structure. For WC stars, comparisons with observed surface abundances also show in general a good agreement (Willis 1991; Maeder & Meynet 1994). In particular, the strong surface Ne–enrichments predicted by the models of WC stars have been confirmed by ISO observations (Willis et al 1997, 1998).

The ratios of the numbers of W–R to O-type stars (W–R/O) or to red supergiants (W-R/RSG), as well as the number of WN with respect to WC stars show a strong correlation with metallicity (Maeder 1991; Maeder & Meynet 1994; Azzopardi et al. 1988; Smith 1988; Massey & Jonhson 1998). For instance, the W–R/O number ratio increases with the metallicity Z of the parent galaxy. The main reason for this trend is the metallicity dependence of the stellar winds, which have a strong impact on the development of the W–R phase and on its lifetime (Smith 1973; Maeder et al. 1980). The higher the metallicity, the stronger is the mass loss by stellar winds and thus the earlier is the entry in the W–R phase for a given star. In addition, the minimum initial mass for forming a W–R star is lowered. This trend will also be responsible for a greater W–R production of radioisotopes in high metallicity regions as, for instance, the inner zones of our Galaxy.

2 THE γ-RAY LINE CONNECTION

^{26}Al is a key radionuclide in the development of γ-ray line astrophysics. This comes from the observation in the present interstellar medium (ISM) of the 1.8 MeV γ-ray line emitted following the de-excitation of the ^{26}Mg produced by the ^{26}Al β-decay.

The data available to-date indicate that the present ISM contains about 2 $M_\odot$ of ^{26}Al, the distribution of which excludes (i) a unique point source in the galactic center, (ii) a strong contribution from the old stellar population of the galactic bulge, and (iii) any class of sources involving a large number of sites with low individual yields, like novae or low-mass AGB stars. In contrast, they favor massive stars (W–R stars and/or SNIb/Ic and SNII) as the ^{26}Al production sites (e.g. Knödlseder et al. 1999).

A detailed discussion of the production of ^{26}Al by the MgAl chain of hydrogen burning developing in non-rotating W–R stars has been conducted recently by Arnould et al. (1997b) and Meynet et al. (1997). It appears that the ^{26}Al yields increase with initial mass and metallicity Z, the Z dependence being approximated by $M_{26}(M_{\rm i}, Z) = (Z/Z_\odot)^2 M_{26}(M_{\rm i}, Z_\odot)$, where $Z_\odot = 0.02$ is the solar metallicity and $M_{26}(M_{\rm i}, Z)$ the mass of ^{26}Al ejected by stars of initial mass $M_{\rm i}$ and metallicity Z. It is worth noticing that the ^{26}Al yields of Meynet et al. (1997) are in qualitative agreement with those of Langer et al. (1995), even if these two sets of models greatly differ in their physical ingredients.

These ^{26}Al yields from non-rotating W–R stars have been used to evaluate quantitatively the virtues of these stars as sources of the 1.8 MeV line in the present ISM. Figure 1 shows the mass of live ^{26}Al deposited by the winds of W–R stars in rings of increasing galactocentric radius. This estimate is based on the metallicity-dependent yields computed by Meynet et al. (1997), and on their assumptions concerning in particular the Initial Mass Function and the galactocentric radius dependence of the metallicity and star formation rate. The signature of the ring of molecular clouds located at the galactocentric radius of about 5 kpc is clearly seen. It is also predicted that more than half of the total ^{26}Al mass is contained within this ring.

The integration of the histogram of Fig. 1 over the galactic radius leads to a total galactic mass of 1.15 $M_\odot$ ejected by the stellar winds of non-rotating W–R stars. Due consideration of various uncertainties leads to masses in the probable 0.4-1.3 $M_\odot$ range (Meynet et al. 1997),

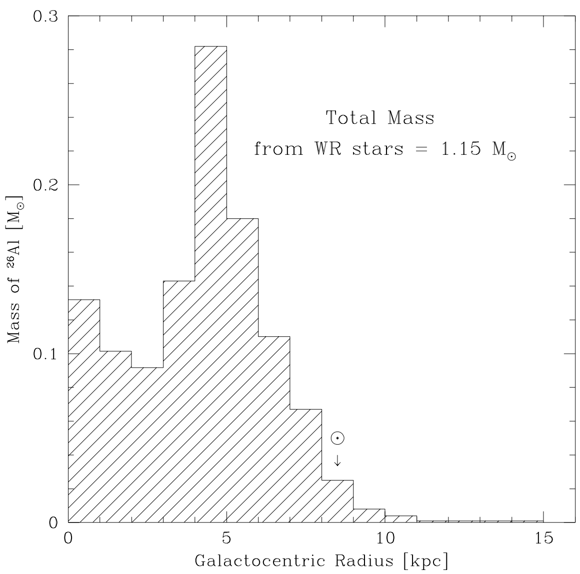

Figure 1: Galactocentric radius dependence of the mass of ^{26}Al ejected by the winds of non-rotating W–R stars. The Galaxy is divided into 15 concentric rings with 1 kpc width.

so that the considered stars might account for 20 to 70% of the present galactic ^{26}Al.

The presently available observations cannot unambiguously disentangle the relative contributions to the present ^{26}Al galactic content of the W–R star winds, of the W–R SNIb/Ic explosions, and of SNII supernovae. In this respect, a recent observation of high value provides an upper limit of about 10^{-5} ph cm^{-2}s^{-1} for the 1.8 MeV luminosity of the γ^2 Vel binary system containing an O-type and a W–R star (of WC8 subtype, Oberlack et al. 1999). In order to evaluate the compatibility of this observation with predictions, at least the initial mass and metallicity of the W–R progenitor, as well as the age of γ^2 Vel have to be known. The proximity of γ^2 Vel justifies the use of solar metallicity stellar models. Non-rotating single star models (Meynet et al. 1994) combined with the position of the O-star component in the HR diagram lead to an age of about 3.6 10^6 yr for the system (De Marco & Schmutz 1999), and an initial W–R mass of about 60 $M_\odot$. Such a W–R progenitor is predicted to have a 1.8 MeV luminosity exceeding the observed upper limit by a factor of about 2. Rotation would lead to a more gradual exposure of ^{26}Al at the stellar surface than in the limit of no rotation (see below). It remains however to be demonstrated through detailed calculations that rotation can indeed cure the γ^2 Vel discrepancy. Let us simply note that the use of rotating star models to estimate the age of the O-type star may also increase its age, modifying the possible range of initial masses for the W–R companion. The binary nature of γ^2 Vel might also provide some remedy if indeed a large enough fraction of the W–R ^{26}Al-loaded ejecta could be accreted by the O-star companion.

2.1 Effect of rotation on the W–R production of ^{26}Al

Rotation induces many dynamical instabilities in stellar interiors, and in particular meridional circulation and shear turbulence (e.g. Zahn 1992). The related mixing of the chemical species can deeply modify the chemical structure of a star and its evolution, and may in particular have important consequences on the ^{26}Al production by W–R stars. At present, very few rotating W–R models address this question in detail (see Langer et al. 1995 for some preliminary

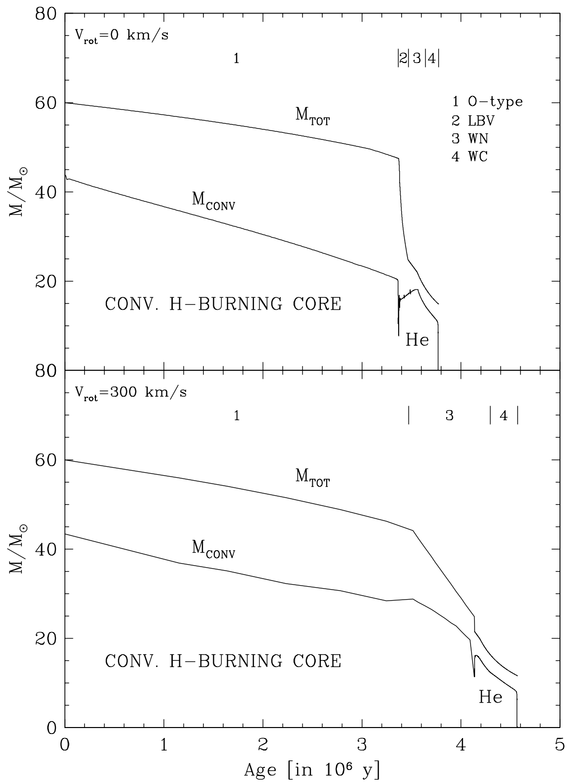

Figure 2: Time evolution of the total mass $M_{\rm TOT}$ and of the mass of the convective core $M_{\rm CONV}$. Various evolutionary stages are indicated at the top of the figure.

results), so that it is premature to quantitatively assess the possible role played by rotation in that respect. However, it seems safe to say that rotation increases the quantity of ^{26}Al ejected by W–R stellar winds. This claim is made plausible by Fig. 2, which shows the structural evolution during their H- and He-burning phases of two 60 $M_\odot$ stars that just differ by their rotational velocities. It appears that

1) The size of the convective core is increased by rotation;

2) During the O-type star phase, the total mass decreases faster in the rotating model;

3) Rapidly rotating stars may enter the W–R phase while still on the Main Sequence. Moreover the surface abundances characteristic of their WNL and WC phases are not due to the mass loss which uncovers core layers, but result from diffusive mixing in the radiative zones. As a consequence, the evolution of the surface abundances are much smoother in rotating models (see Fig. 3);

4) The W–R lifetime increases with the initial rotational velocity. In particular the WN stage during which ^{26}Al is ejected lasts much longer, so that much more mass is ejected during this phase. As a numerical example, the non-rotating model sketched in Fig. 2 ejects about 7 $M_\odot$ during the WN phase, while about 28 $M_\odot$ are ejected by the rotating model during the same phase.

The inference that rotation can enhance the ^{26}Al yields of W–R stars is confirmed by the numerical simulations of Langer et al. (1995). Rotation also lowers the minimum initial mass of single stars which can go through a W–R stage with a concomitant ejection of ^{26}Al. This likely contributes to the net amount of ^{26}Al ejected by W–R stars in the ISM, which may be of relevance both to cosmochemistry and to γ-ray line astrophysics.

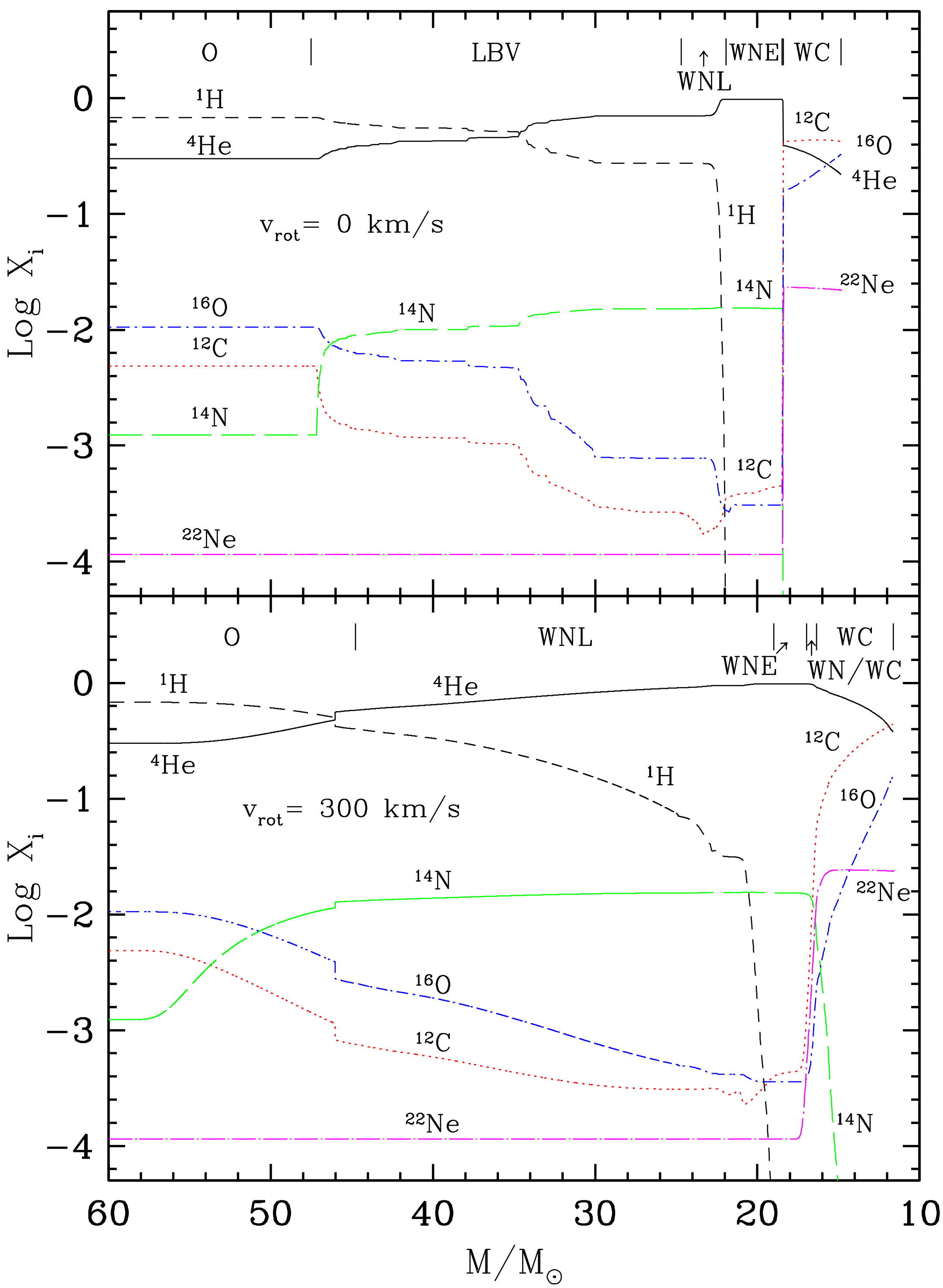

Figure 3: Evolution of the abundances at the surface of a 60 $M_\odot$ star as a function of the remaining stellar mass for different initial rotational velocities $v_{\rm rot}$. The portions of the evolution during which the star may be considered as an O-type star, a LBV and a W–R star are indicated. During the W–R phase, the WN, the transition “WN/WC” and the WC phases are identified.

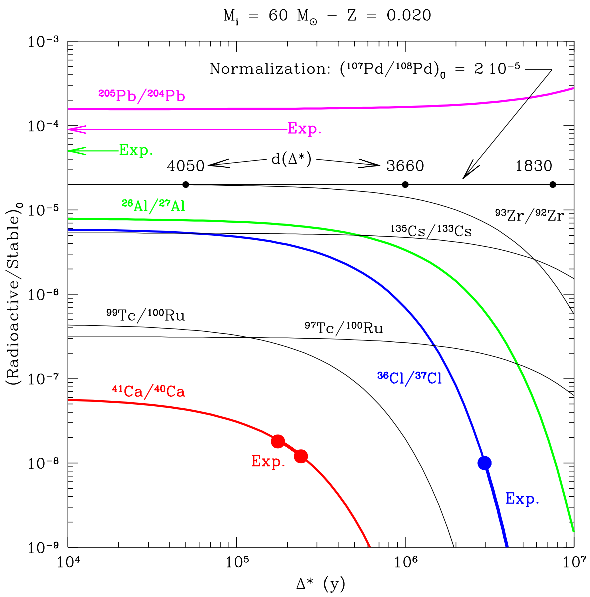

Figure 4: Abundance ratios $(\mathrm{R/S})_0$ of various radionuclides R relative to stable neighbours S versus Δ^* (see main text) for the 60 $\mathrm{M}_\odot$ model star with $Z = 0.02$. All the displayed ratios are normalized to $(^{107}\mathrm{Pd}/^{108}\mathrm{Pd})_0 = 2\,10^{-5}$ (e.g. Wasserburg 1985) through the application of a common dilution factor $d(\Delta^*)$. The values of this factor are indicated on the Pd horizontal line for 3 values of Δ^*. Other available experimental data (labelled Exp) are displayed. They are adopted from MacPherson et al. (1995) for Al, Srinivasan et al. (1994) for Ca, Murty et al. (1997) for Cl, and Huey & Kohman (1972) for Pb (see Arnould et al. 1997ab for more details)

2.2 Effect of binarity on the W–R production of ^{26}Al

Tidal interactions in close binary systems may considerably modify the evolution of the two stellar components with respect to the one they would experience as isolated stars. Mass transfer by Roche Lobe Overflow can mimic a strong stellar wind, and thus reduce the critical initial mass for producing single W–R stars. Before any mass transfer, tidal effects are also expected to deform the star and therefore induce instabilities reminiscent of those induced by rotation. To our knowledge, the latter effect has never been studied in any detail, even if it might have important consequences, like the homogenization of the stars, and the related inhibition of mass transfer. Other effects remain to be explored, like the impact of colliding winds on the mass transfer process, or even the very nature of the grains which can condense in colliding winds. Thus the effect of binarity on the W–R star formation and evolution, and on the corresponding ^{26}Al production cannot be evaluated with confidence at this time. Some preliminary estimates (Braun & Langer 1995) lead to the conclusion that 'only for stars with masses ≤ 40 $\mathrm{M}_\odot$, binarity has the potential to increase the ^{26}Al yield compared to the single star case'. The fact that the situation may be quite different in more massive stars can be interpreted in the following way: after their Main Sequence, single high mass stars go through a LBV phase characterized by especially high stellar winds. Additional mass losses triggered by binarity would thus not induce more than a perturbation in the evolution of these stars. In contrast, lower initial mass stars not suffering the LBV winds would be drastically affected by Roche Lobe Overflow mass transfer, which acts as a strong wind not operating if the corresponding stars were isolated.

The extent in the reduction of the ^{26}Al that can be ejected in the ISM by $M > 40$ $\mathrm{M}_\odot$ W–R members of binary systems cannot be assertained at this point. It has clearly to depend on the fraction of the mass lost by the W–R star which is accreted by its companion, and

thus withdrawn from the ISM. In this scenario, however, one may wonder about the fate of the accreting companion, and about its net production or destruction of ^{26}Al resulting from its evolution (see Langer et al. 1998). Clearly, the effect of binarity on the net ^{26}Al outcome by W–R stars largely remains to be studied.

3 THE METEORITIC CONNECTION

The chemical composition of W–R stellar winds may be relevant to the understanding of some isotopic anomalies observed in meteorites (Arnould et al. 1997ab). In particular it appears that a series of radionuclides have decayed in situ in some of them (see the review by Podosek & Nichols 1997). This fact may be interpreted as resulting from the injection into the proto-solar nebula of these radioisotopes by one or a few nucleosynthetic source(s). It is interesting to mention that such an observation puts some constraints on Δ^*, the time elapsed between the last astrophysical event(s) able to affect the composition of the solar nebula and the solidification of some of its material. This time must be shorter than the time required for the decay of the radionuclide if at least part of it has to be trapped in live form in meteorites.

A detailed study of the production by non-rotating W–R stars of short-lived radionuclides of astrophysical and cosmochemical interest has been conducted by Arnould et al. (1997b). In short, their main results may be summarized as follows:
(1) The neutrons released by $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ during the He-burning phase of the considered stars are responsible for a s-type process leading to the production of a variety of $A > 30$ radionuclides. In the absence of any chemical fractionation between the relevant elements, it is demonstrated that ^{36}Cl, ^{41}Ca and ^{107}Pd can be produced by this s-process in a variety of W–R stars of the WC subtype with different initial masses and compositions at a *relative* level compatible with the meteoritic observations. For a 60 $M_\odot$ star with solar metallicity, Fig. 4 shows that this agreement can be obtained for a time $\Delta^* \approx 2 \times 10^5$ y, where Δ^* designates the time elapsed between the last astrophysical event(s) able to affect the composition of the solar nebula and the solidification of some of its material. More details concerning other model stars are given by Arnould et al. (1997b);
(2) To the above list of radionuclides, one of course has to add ^{26}Al (see above). The canonical value $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 = 5 \times 10^{-5}$ (MacPherson et al. 1995; the subscript 0 refers to the start of the solidification sequence in the solar system), while not reached in the 60 $M_\odot$ star displayed in Fig. 4, can be obtained from the winds of $M \geq 60$ $M_\odot$ stars with $Z > Z_\odot$ under the same type of assumptions as the ones adopted to construct Fig. 4. Let us also note that the W–R models can account for the correlation between ^{26}Al and ^{41}Ca observed in some meteorites (Sahijpal et al. 1998);
(3) Too little ^{60}Fe is synthesized;
(4) An amount of ^{205}Pb that exceeds largely the experimental upper limit set by Huey & Kohman (1972), but which is quite compatible with the value reported by Chen & Wasserburg (1987), is obtained not only for the model star displayed in Fig. 4, but also for the other cases considered by Arnould et al. (1997b).
(5) More or less large amounts of ^{93}Zr, ^{97}Tc, ^{99}Tc and ^{135}Cs can also be produced in several cases, but these predictions cannot be tested at this time due to the lack of reliable observations.

It has to be remarked that the above conclusions are derived without taking into account the possible contribution from the material ejected by the eventual SNIb/c explosion of the considered W–R stars. This SN might add its share of radionuclides that are not produced abundantly enough prior to the explosion. This concerns in particular ^{53}Mn, ^{60}Fe or ^{146}Sm.

One has also to acknowledge that the above conclusions sweep completely under the rug the possible role of rotation and binarity in the W–R yields.

¿From the results reported above, one can try estimating if indeed there is any chance for the contamination of the protosolar nebula with isotopically anomalous W–R wind material at an *absolute* level compatible with the observations. In the framework of Fig. 4, this translates into the possibility of obtaining reasonable dilution factors $d(\Delta^*)$. A qualitative discussion of this highly complex question based on a quite simplistic scenario is presented by Arnould et al. (1997b). In brief, it is concluded that astrophysically plausible situations may be found in which one or several W–R stars with masses and metallicities in a broad range of values could indeed account for some now extinct radionuclides that have been injected live into the forming solar system (either in the form of gas or grains). Of course, a more definitive conclusion would have to await the results of a more detailed model that takes into account the high complexity of the W–R circumstellar shells, and of their interaction with their surroundings, demonstrated by observation and suggested by numerical simulations. Concomitantly, the possible role of W–R stars, either isolated or in OB associations, as triggers of the formation of some stars, and especially of low-mass stars, should be scrutinized.

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